Diffraction model of a plenoptic camera for in-situ space exploration

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MOTIVATION

- DLR investigates the usage of light field cameras (plenoptic cameras) for future planetary exploration missions
- Disadvantages of conventional hand lens imagers (HLIs): physically limited in their depth of field, which requires a focusing mechanism; multiple images need to be recorded in order to create a depth map
- Advantages of light field cameras: extended depth of field in comparison to conventional cameras, possibility of creating single shot depth images with a single, passive camera
- For in-depth understanding of plenoptic cameras: detailed mathematical description of a plenoptic camera is given (geometric and diffraction model)

GEOMETRIC DESCRIPTION OF A PLENOPTIC SYSTEM

- First order estimation of the optical system of a light field camera: ray tracing $\rightarrow$ information about the footprints that a light ray makes by passing the system

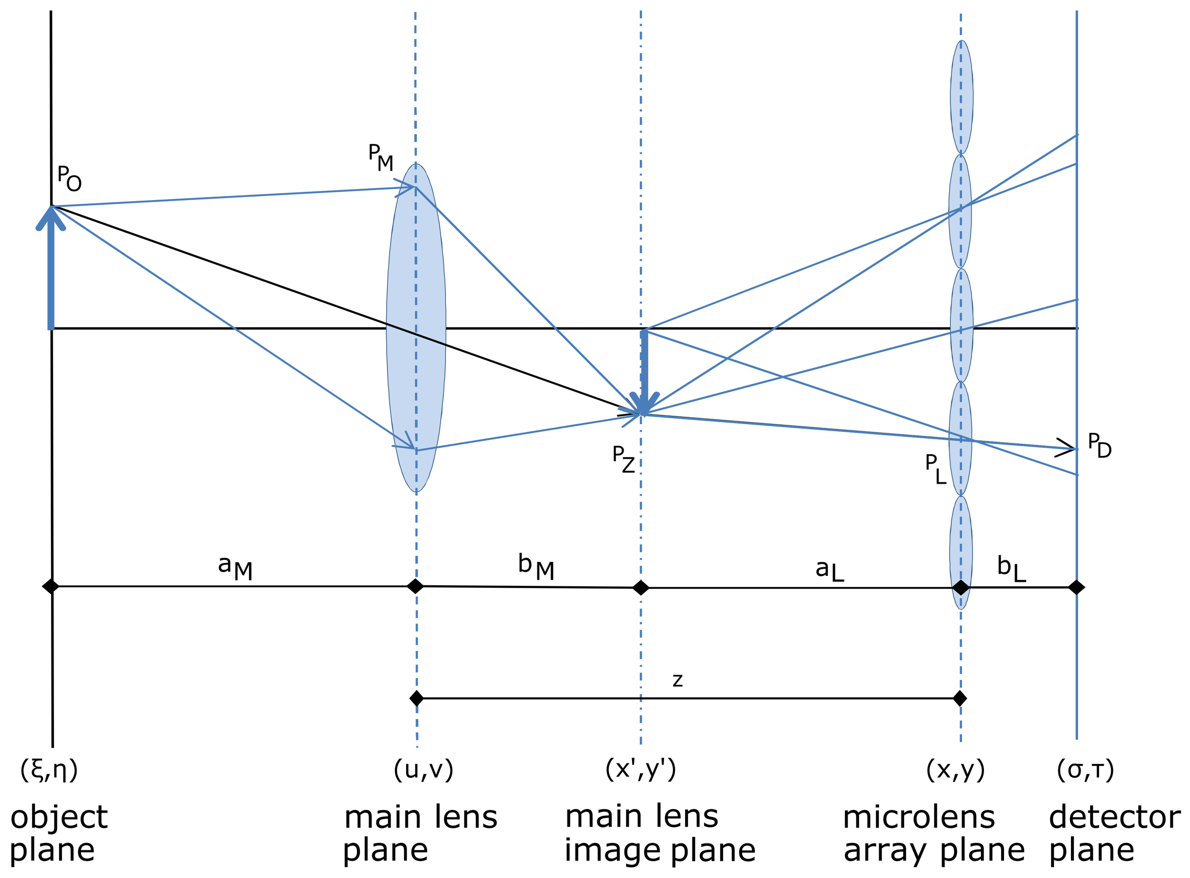

Figure 1: Focused plenoptic camera

- Projection from object plane to detector plane: $P_O \rightarrow P_D$

$$P_D^i\left(\sigma^i, \tau^i, b_M + b_L + a_L\right) = \left(-\frac{\xi f_M b_L}{a_M f_M - z(a_M - f_M)} + \frac{x^i_{off}(f_M - a_M)b_L}{a_M f_M - z(a_M - f_M)}, -\frac{\eta f_M b_L}{a_M f_M - z(a_M - f_M)} + \frac{y^i_{off}(f_M - a_M)b_L}{a_M f_M - z(a_M - f_M)}, b_M + b_L + a_L\right)$$

- Projection from detector plane to object plane: $P_D \rightarrow P_O$

$$P_O\left(\xi, \eta, -a_M\right) = \left(x^i_{off} - \frac{\sigma^i z}{b_L} + a_M\left(\frac{\sigma^i z}{f_M b_L} - \frac{\sigma^i}{b_L} - \frac{x^i_{off}}{f_M}\right), y^i_{off} - \frac{\tau^i z}{b_L} + a_M\left(\frac{\tau^i z}{f_M b_L} - \frac{\tau^i}{b_L} - \frac{y^i_{off}}{f_M}\right), -a_M\right)$$

- Deduction of distance a_M for two given image points of the same object

$$a_M = f_M\left[1 + \frac{f_M}{(z - f_M) - b_L \frac{x^1_{off} - x^2_{off}}{\sigma^1 - \sigma^2}}\right]$$

- In-situ planetary exploration with Hand Lens Imagers is subject to the challenges and limitations of close range imaging
- It appears that plenoptic cameras are a promising concept for future HLIs

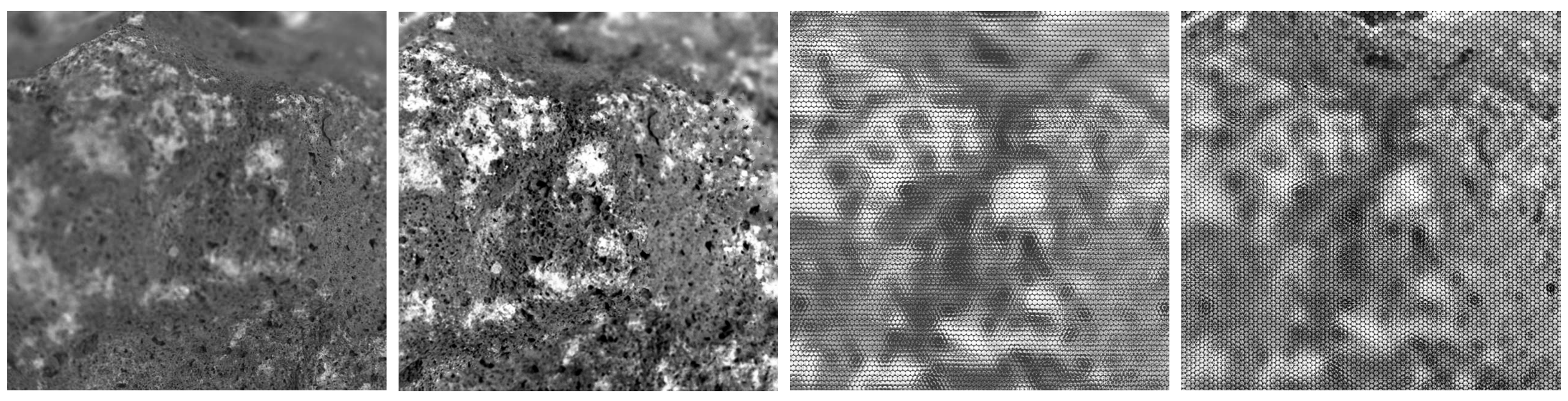

Figure 2: Example of an in-situ scene with a recorded rock surface with some depth extend. From left: 1) conventional camera image. 2) multi-focus plenoptic camera image with an extended depth of field. 3) simulated raw plenoptic image with depth. 4) real raw plenoptic image

WAVE-OPTICAL DESCRIPTION OF A PLENOPTIC SYSTEM

- Pixel sizes range in the order of some visible light wavelengths, apertures are low $\rightarrow$ effects of diffraction can be observed, a wave-theoretical approach is convenient
- PSF by Kirchhoff: Amplitude right in front of the detector plane

$$U_\lambda^D\left(\sigma', \tau'\right) = \iint d\xi d\eta h_\lambda(\xi, \eta, \sigma', \tau') U_\lambda^O(\xi, \eta)$$

with the PSF

$$h_\lambda(\xi, \eta, \sigma', \tau') = \frac{a_M \cdot z \cdot b_L}{-i\lambda^3} \cdot e^{\frac{2\pi i}{\lambda}(n_M \Delta_M + n_L \Delta_L)} \times \sum_{k,l=0}^{\#ML-1} \iint dx'_k dy'_l e^{-\frac{\pi i}{\lambda f_L}(x'^2_k + y'^2_l)} \iint dudve^{-\frac{\pi i}{\lambda f_M}(u^2+v^2)} \frac{e^{\frac{2\pi i}{\lambda}(|\overrightarrow{r_O}| + |\overrightarrow{r_M}| + |\overrightarrow{r_L}|)}}{|\overrightarrow{r_O}|^2 |\overrightarrow{r_M}|^2 |\overrightarrow{r_L}|^2}$$

- PSF by Fresnel: Amplitude right in front of the detector plane

$$U_\lambda^D\left(P_D\right) = \iint d\xi \; d\eta \; h_\lambda\left(P_O, P_D\right) \cdot U_\lambda^O(P_D)$$

with

$$h_\lambda(P_O, P_D) = \frac{e^{\frac{2\pi i}{\lambda}(a_L + z + b_L)}}{-i\lambda^3 \cdot a_M \cdot z \cdot b_L} \cdot e^{\frac{2\pi i}{\lambda}(n^M_\lambda \Delta^M_0 + n^L_\lambda \Delta^L_0)} \cdot e^{\frac{\pi i}{\lambda b_L}(\sigma'^2 + \tau'^2)} e^{\frac{\pi i}{\lambda a_M}(\xi^2 + \eta^2)} \times \sum_{k,l=0}^{\#ML-1} \iint dx'_k dy'_l e^{\frac{-2\pi i}{\lambda b_L}(\sigma' x'_k + \tau' y'_l)} \iint du \; dv \; e^{\frac{-2\pi i}{\lambda z}(x'_k u + y'_l v)} \cdot e^{\frac{-2\pi i}{\lambda a_M}(u\xi + v\eta)}$$

Fresnel: quicker than Kirchhoff, BUT not convenient for close range

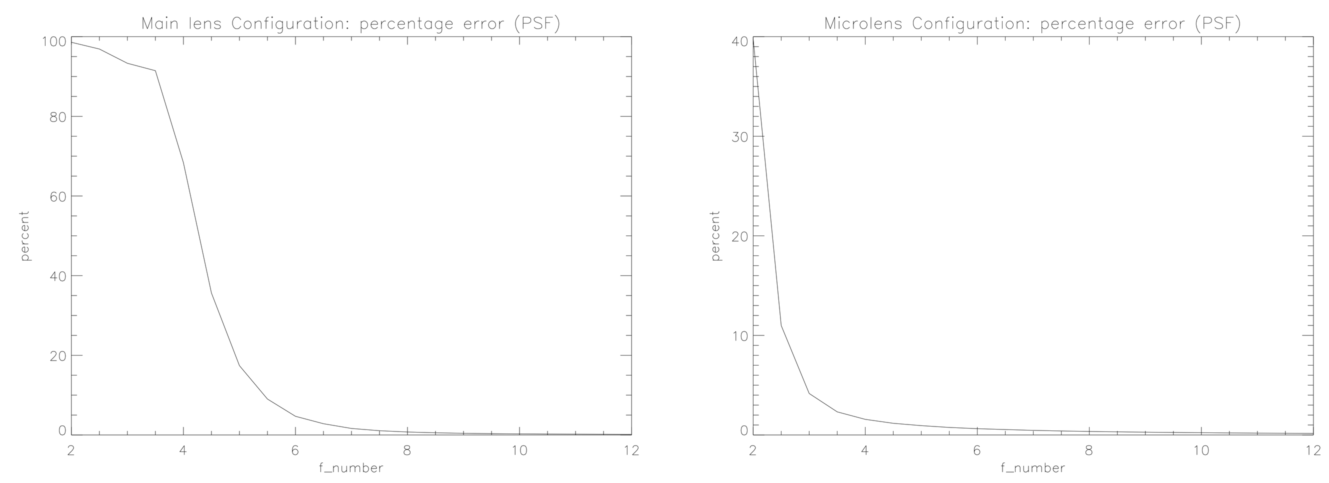

Figure 3: Percentage of error between the PSF by Kirchhoff and Fresnel. Left: main lens; Right: microlens

- Comparison between geometric and wave-optical approach: Light spot captured by a plenoptic camera simulated by
  - geometric approach (left image, computing time (ct) few seconds)
  - wave-optical approach (middle: Kirchhoff-Fresnel combination, ct: 26 h, right: solely Kirchhoff, ct: 50 h)
  - geometric model might be a convenient solution for a quick simulation of the camera performance, but results are fraught with significant errors

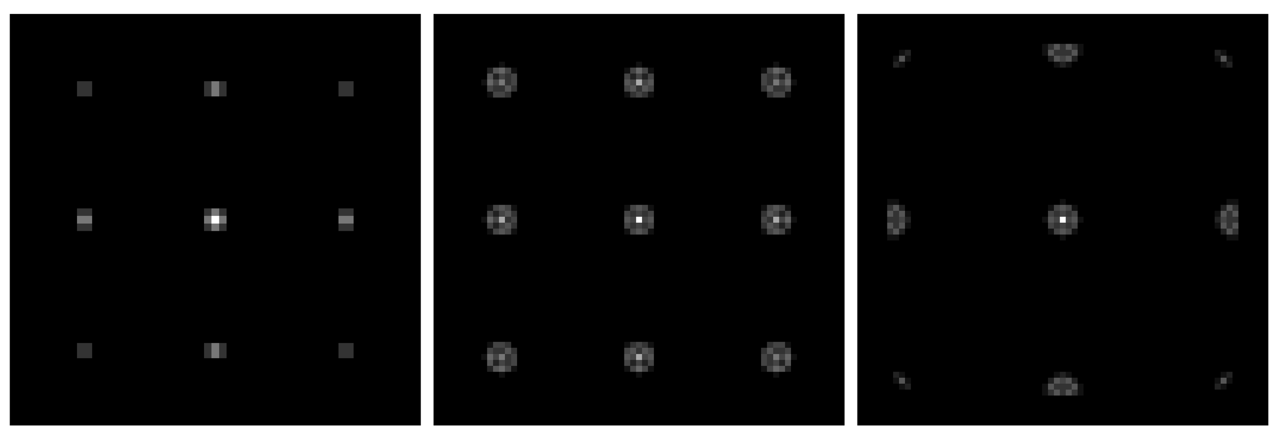

Figure 4: A light spot is captured by an array of 3×3 microlenses. From left: 1) geometric model. 2) wave-optical approach with Kirchhoff (main lens) and Fresnel (microlens). 3) wave-optical approach solely by Kirchhoff.

SUMMARY AND OUTLOOK

- Plenoptic cameras are an interesting concept for future HLIs
- A first step towards plenoptic hand lens imagers: mathematical description of a geometric and a wave-optical model of a plenoptic camera was outlined
- in close-range it would be wise not to dispense with the diffraction effects
- In future: hybrid formulation of geometric and wave-optical methods $\rightarrow$ combination of advantages: short computing time on the one hand and physical correctness on the other hand

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